Measurement of the $B^0 \to D^{*-}D_s^{*+}$ and $D_s^+ \to \phi\pi^+$ Branching Fractions

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We present measurements of the branching fractions $\mathcal{B}(B^0 \to D^{*-}D_s^{*+})$ and $\mathcal{B}(D_s^+ \to \phi\pi^+)$, based on 123×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- B factory. A partial reconstruction technique is used to measure $\mathcal{B}(B^0 \to D^{*-}D_s^{*+})$ and the decay chain is fully reconstructed to measure the branching fraction product $\mathcal{B}(B^0 \to D^{*-}D_s^{*+}) \times \mathcal{B}(D_s^+ \to \phi\pi^+)$. Comparing these two measurements provides a model-independent determination of the $D_s^+ \to \phi\pi^+$ branching fraction. We obtain $\mathcal{B}(B^0 \to D^{*-}D_s^{*+}) = (1.88 \pm 0.09 \pm 0.17)\%$ and $\mathcal{B}(D_s^+ \to \phi\pi^+) = (4.81 \pm 0.52 \pm 0.38)\%$, where the first uncertainties are statistical and the second systematic.

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Published measurements of $\mathcal{B}(B^0 \to D^{*-}D_s^{*+})$ [1, 2] are limited by the uncertainties on the D_s^+ partial decay rates. A substantial improvement can therefore be obtained using a partial reconstruction technique where the D_s^+ is not explicitly reconstructed. The measurement of $\mathcal{B}(B^0 \to D^{*-}D_s^{*+})$ provides a test of the details of the factorization assumption [3] in the relatively high q^2 regime [4]. Partial reconstruction in addition allows an unbiased measurement of the $D_s^+ \to \phi\pi^+$ branching fraction, which has important implications for a wide range of D_s and B physics, as most of the D_s decay branching fractions are normalized to it [1]. As an example, an improved measurement of $\mathcal{B}(D_s^+ \to \phi\pi^+)$ would reduce the experimental uncertainty on the constraint on the Unitary Triangle parameter γ from the measurement of the CP violating asymmetry in $B^0 \to D^{*\pm}\pi^\mp$ decays [5].

We used $(123 \pm 1) \times 10^6$ $B\overline{B}$ decays collected at the PEP-II asymmetric-energy e^+e^- B factory with the *BABAR* detector, which is described in detail elsewhere [6]. We provide here a brief description of the detector components relevant for this analysis. Charged-particle trajectories are measured by a silicon vertex tracker (SVT) and a drift chamber (DCH) immersed in a 1.5 T solenoidal magnetic field. The five-layer SVT enables tracks with low transverse momentum to be reconstructed. The energy and direction of photons and electrons are measured by a CsI(Tl)-crystal electromagnetic calorimeter (EMC). Charged-particle identification is obtained from the measurement of energy loss in the tracking system, and from the measurement of the number and the angle of Cherenkov photons in a ring-imaging Cherenkov detector (DIRC).

To study efficiencies and backgrounds and to validate the analysis we use several event samples produced with a Monte Carlo (MC) simulation of the *BABAR* detector based on GEANT4 [7] and reconstructed through the same chain as the data.

The $B^0 \to D^{*-}D_s^{*+} \to (D_s^+\gamma)(\overline{D}^0\pi^-)$ decay [8] is reconstructed using two different methods. The first method combines the fully reconstructed D^{*-} decay with the photon from the $D_s^{*+} \to D_s^+\gamma$ decay, without explicit D_s^+ reconstruction. Denoting the measured yield by $\mathcal{N}_{D_s}$,

we can write:

$$\mathcal{B}(B^0 \to D^{*-}D_s^{*+}) \equiv \mathcal{B}_1 = \frac{\mathcal{N}_{D_s}}{\mathcal{K}\sum_i(\varepsilon_i\mathcal{B}_i)}. \quad (1)$$

Here $\mathcal{K} \equiv 2N_{B\overline{B}}f_{00}\mathcal{B}(D_s^{*+} \to D_s^+\gamma)\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-)$, $N_{B\overline{B}}$ is the number of B-meson pairs, $f_{00} = 0.499 \pm 0.012$ [9] is the fraction of $\Upsilon(4S) \to B^0\overline{B}^0$ decays, $\mathcal{B}_i$ is the branching fraction of $\overline{D}^0$ decay mode i, ε_i is the efficiency for partially reconstructing the B^0 with a photon, a low momentum ("soft") pion and a $\overline{D}^0$ reconstructed in mode i.

The second method, based on full reconstruction of the $B^0 \to D^{*-}D_s^{*+}$ decay via $D_s^+ \to \phi\pi^+$ ($\phi \to K^+K^-$), measures the branching fraction product $\mathcal{B}_2 \equiv \mathcal{B}(B^0 \to D^{*-}D_s^{*+}) \times \mathcal{B}(D_s^+ \to \phi\pi^+)$:

$$\mathcal{B}_2 = \frac{\mathcal{N}_{D_s \to \phi\pi}}{\mathcal{K}\mathcal{B}(\phi \to K^+K^-)\sum_i(\varepsilon_i'\mathcal{B}_i)}, \quad (2)$$

where $\mathcal{N}_{D_s \to \phi\pi}$ is the number of reconstructed decays and ε_i' is the efficiency for fully reconstructing the B^0, including reconstruction of $\phi \to K^+K^-$. The $D_s^+ \to \phi\pi^+$ branching fraction is measured from the $\mathcal{B}_2/\mathcal{B}_1$ ratio:

$$\mathcal{B}(D_s^+ \to \phi\pi^+) = \frac{\mathcal{B}_2}{\mathcal{B}_1} = \frac{\mathcal{N}_{D_s \to \phi\pi}\sum_i(\varepsilon_i\mathcal{B}_i)}{\mathcal{N}_{D_s}\mathcal{B}(\phi \to K^+K^-)\sum_i(\varepsilon_i'\mathcal{B}_i)}, \quad (3)$$

where the factor $\mathcal{K}$ drops out. Although the efficiencies ε_i and ε_i' are in general different, they include common factors and many systematic uncertainties cancel in the ratio.

To extract the signal in partially reconstructed events, we compute the "missing mass" recoiling against the $D^{*-}\gamma$ system, assuming that a $B^0 \to D^{*-}\gamma X$ decay took place:

$$m_{\text{miss}} = \sqrt{(E_B - E_{D^*} - E_\gamma)^2 - (\mathbf{p}_B - \mathbf{p}_{D^*} - \mathbf{p}_\gamma)^2}, \quad (4)$$

where all quantities are defined in the $\Upsilon(4S)$ center-of-mass (CM) frame. While the photon and D^{*-} energies (E_γ, E_{D^*}) and their three-momenta ($\mathbf{p}_\gamma$, $\mathbf{p}_{D^*}$) are measured, kinematical constraints are needed to determine the B four-momentum (E_B, $\mathbf{p}_B$). In order to do that we

equate the B-meson energy with E_{beam}, the beam energy in the CM frame, and calculate the cosine of the opening angle ϑ_{BD*} between the B and the D^{*-} momentum vectors from 4-momentum conservation in the $B^0 \to D^{*-}D_s^{*+}$ decay. This leaves the azimuthal angle of the B meson around the D^{*-} direction as the only undetermined parameter in the kinematics of the decay. MC studies show that an arbitrary choice of this angle (we fix $\cos\phi_{BD*} = 0$) introduces a negligible spread (of the order of 1.5 MeV/c^2) in the m_{miss} distribution. The m_{miss} distribution of signal events peaks at the nominal D_s^+ mass [1] with a width of about 15 MeV/c^2.

We suppress unphysical $D^{*-}\gamma$ combinations by requiring $|\cos\vartheta_{BD*}| \le 1.2$ and events from $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ production by requiring the ratio of the second to the zeroth Fox-Wolfram moments [10] to be less than 0.3.

D^{*-} candidates are reconstructed in the $\overline{D}^0\pi^-$ mode using $\overline{D}^0$ decays to $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$ and $K_s^0\pi^+\pi^-$, listed here in order of decreasing purity. The χ^2 probabilities of both the D^0 and D^* vertex fits are required to be greater than 1%. The D^{*-} momentum in the $\Upsilon(4S)$ frame must satisfy $1.4 < p_{D*} < 1.9$ GeV/c. We require the reconstructed mass of the D^0 to be within 3 standard deviations ($\sigma_{m_{D^0}}$) of the measured peak value, and $Q_{D*} \equiv m_{D*} - m_{D^0} - m_\pi$ to satisfy $Q_{\text{lo}} < Q_{D*} < Q_{\text{hi}}$, where the choice of limits $Q_{\text{lo}} = 4.10 - 5.20$ MeV/c^2 and $Q_{\text{hi}} = 6.80 - 7.90$ MeV/c^2 around the nominal value $Q_{D*}^{\text{PDG}} = 5.851$ MeV/c^2 depends on the D^0 decay mode. Kaon identification is required in $K^+\pi^-\pi^0$ and $K^+\pi^-\pi^+\pi^-$ modes. The K_s^0 from the $K_s^0\pi^+\pi^-$ mode must have an invariant mass within 15 MeV/c^2 of the nominal K_s^0 mass and a flight length greater than 3 mm.

If more than one D^{*-} candidate is found, we first retain those that have the $\overline{D}^0$ reconstructed in the decay mode with the highest expected purity. If ambiguities persist at this stage, we choose the best candidate based on the track quality of the soft pion and finally on the minimum value of $\chi^2 = [(Q_{D*} - Q_{D*}^{\text{PDG}})/\sigma_{Q_{D*}}]^2 + [(m_{D^0} - m_{D^0}^{\text{PDG}})/\sigma_{m_{D^0}}]^2$, where $\sigma_{Q_{D*}}$ is the measured resolution on Q_{D*}.

Photon candidates are chosen from clusters of energy deposited in the EMC that are not associated with any charged track. The energy spectrum of photons from the $D_s^{*+} \to D_s^+\gamma$ decay is rather soft ($E_\gamma \lesssim 0.4$ GeV) and this makes controlling the background due to random photon associations one of the main challenges in the analysis. We require $E_\gamma > 142$ MeV and use the energy profile of the cluster to refine the photon selection, requiring a minimum cluster lateral moment [11] of 0.016, and a minimum Zernike moment A_{20} [12] of 0.82. We also reject photon candidates that form in combination with any other photon in the event a π^0 whose invariant mass is between 115 and 155 MeV/c^2 and whose momentum in the CM frame is greater than 200 MeV/c. This selection retains more than one photon candidate in about 10 % of the events. In these occurrences we choose the one that

maximizes the value of a likelihood ratio based on the energy and the shape of the reconstructed cluster.

The cuts are chosen to maximize the expected statistical significance of the selected signal using MC. The combinatorial background is dominated by $B^0\overline{B}^0$ events. None of the background components peak at the D_s^+ mass in the m_{miss} distribution. The reconstruction and selection efficiency, evaluated on simulated events, is $\langle\varepsilon\mathcal{B}\rangle \equiv \sum_i (\varepsilon_i\mathcal{B}_i) = (5.15 \pm 0.03) \times 10^{-3}$.

We extract the signal yield using an unbinned maximum-likelihood fit to the m_{miss} distribution. The signal peak is well described by a Gaussian probability density function (p.d.f.). We parameterize the combinatorial background with the threshold function $B(m_{\text{miss}}) = B_0(1 - e^{-(m_{\text{max}} - m_{\text{miss}})/b})(m_{\text{miss}}/m_{\text{max}})^c$. Fig. 1 shows the result of the fit to the missing-mass distribution. The width of the Gaussian signal distribution is taken from MC simulation. The signal yield is
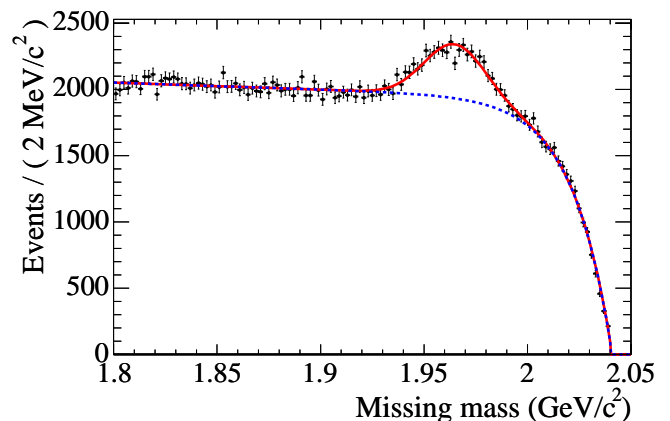

FIG. 1: Fit (solid line) to the measured missing-mass distribution. The background component is shown as the dashed line.

$\mathcal{N}_{D_s} = 7488 \pm 342$ events, corresponding to a branching fraction $\mathcal{B}(B^0 \to D^{*-}D_s^{*+}) = (1.88 \pm 0.09)$ %, where the quoted error is purely statistical.

We now describe the full reconstruction of the $B^0 \to D^{*-}D_s^{*+} \to (D_s^+\gamma)(\overline{D}^0\pi^-)$ chain, with $\overline{D}^0$ decaying into the four modes considered, and $D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$. Two kinematical variables are used: $\Delta E \equiv E_B - E_{\text{beam}}$ and the energy-substituted mass $m_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - \mathbf{p}_B^2}$. The two variables have very little correlation; for signal events ΔE peaks around zero and m_{ES} at the B-meson mass. After applying selection cuts (described below) on the D_s^{*+} and D^{*-} candidates, we retain the combination with the smallest value of $|\Delta E|$. The number of fully reconstructed B^0 candidates is then obtained from a fit to the m_{ES} spectrum.

The selection of D^{*-} candidates and most of the requirements on photon candidates are identical to those adopted in the partial reconstruction analysis. Due to the additional kinematical constraints on fully reconstructed B decays, the combinatorial background level is much

smaller; we can therefore relax the requirement on E_γ, thus improving the statistical significance of our sample. We reconstruct ϕ candidates from pairs of oppositely charged tracks, with at least one track satisfying kaon selection criteria; D_s^+ candidates are formed by combination with an additional track, with charge opposite to the soft pion from the D^{*-} decay. A mass within ± 50 MeV/c^2 of the nominal D_s^+ mass [1] is required. Finally, D^{*-} and D_s^{*+} mass constraints are imposed in order to improve the m_{ES} and ΔE resolution of the B^0 candidate. We require the $m_{D_s^*} - m_{D_s}$ mass difference to be between 125 and 160 MeV/c^2, the reconstructed ϕ mass to be between 1.008 and 1.035 GeV/c^2, E_γ to be greater than 90 MeV, and $|\Delta E|$ to be less than 50 MeV.
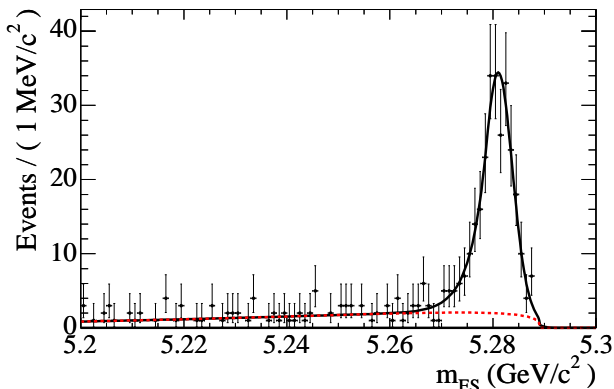

FIG. 2: Fit (solid line) to the measured m_{ES} distribution. The background component is shown as the dashed line.

We perform an unbinned maximum-likelihood fit to the m_{ES} distribution with the sum of a Crystal Ball [13] function, and a threshold ARGUS [14] function; the latter accounts for the combinatorial background. From the fit to the data sample, shown in Fig. 2, we obtain (247 ± 19) events in the signal region defined as $m_{ES} > 5.27$ GeV/c^2.

MC studies indicate a peaking contribution due to real $B^0 \to D^{*-}D_s^{*+}$ events, where either the $\overline{D}^0$ does not decay into the reconstructed modes, or the D_s^+ does not decay into $\phi\pi^+$. We subtract the peaking background applying a correction factor to take into account that the values of the $B^0 \to D^{*-}D_s^{*+}$ and $D_s^+ \to \phi\pi^+$ branching fractions that we have measured are different from those used in the simulation, with an iterative procedure. The resulting number of peaking background events expected in the data sample is 35 ± 6 events; this uncertainty is taken into account in the systematic error. After subtraction of the peaking background events, the final signal event yield is $\mathcal{N}_{D_s \to \phi\pi} = (212 \pm 19)$. Taking into account the reconstruction and selection efficiency $\langle \varepsilon'\mathcal{B} \rangle \equiv \sum_i (\varepsilon_i'\mathcal{B}_i) = (6.16 \pm 0.24) \times 10^{-3}$, evaluated on simulated events, we determine $\mathcal{B}_2 = \mathcal{B}(B^0 \to D^{*-}D_s^{*+}) \times \mathcal{B}(D_s^+ \to \phi\pi^+) = (8.81 \pm 0.86) \times 10^{-4}$, where the error is statistical only.

TABLE I: Summary of systematic uncertainties.

Source	$\mathcal{B}_1$ [%]	$\mathcal{B}_2$ [%]	$\mathcal{B}_2/\mathcal{B}_1$ [%]
p.d.f. modeling	4.8		4.8
Comb. background		2.9	2.9
MC statistics	0.6	3.2	3.3
Peaking background		2.8	2.8
B counting	1.1	1.1	
f_{00}	2.4	2.4	
Soft pion efficiency	2.2	2.2	
D^{*-} Tracking efficiency	2.4	2.4	
D^{*-} Vertexing efficiency	2.0	2.0	
D_s^+ Tracking efficiency		2.6	2.6
D_s^+ Vertexing efficiency		2.0	2.0
Photon efficiency	1.8	1.8	
π^0 eff. ($\overline{D}^0 \to K^+\pi^-\pi^0$)	1.2	1.2	
π^0 veto	4.7	4.7	
Particle identification	0.4	0.4	
Polarization uncertainty	0.8	0.8	
D^0 branch. fract. [1]	3.2	3.2	
$\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-)$ [1]	0.7	0.7	
$\mathcal{B}(D_s^{*+} \to D_s^+\gamma)$ [15]	0.8	0.8	
$\mathcal{B}(\phi \to K^+K^-)$ [1]		1.2	1.2
Total systematic error	9.1	10.7	7.9

The main sources of systematic uncertainties on the $B^0 \to D^{*-}D_s^{*+}$ branching fraction measurement are listed in the second column ($\mathcal{B}_1$) of Table I. We compared the resolution of the Gaussian p.d.f. in data and MC by fitting the missing mass distribution in the very clean sample of fully reconstructed $B^0 \to D^{*-}D_s^{*+}$ events. We disentangle in this way the effect of the experimental resolution on the width of the signal peak from the correlations in the fit between the width and the background parameters. We obtain $\sigma_{data}/\sigma_{MC} = (1.01 \pm 0.05)$. We repeated the m_{miss} fits changing the Gaussian width by this uncertainty, and varying the background parameters by their errors. We assign the maximum deviation as systematic uncertainty, labelled in Table I as "p.d.f. modeling". The MC statistics uncertainty is the statistical error on the efficiency determination. The systematic uncertainties due to tracking, vertexing, photon and π^0 reconstruction efficiencies, and particle identification are evaluated using independent control samples. The effect of the π^0 veto is evaluated from fully reconstructed events. The uncertainty due to the dependence of the efficiency on the polarization of the $B^0 \to D^{*-}D_s^{*+}$ decay is assessed from MC samples generated with complete longitudinal and transverse polarization. In the full reconstruction analysis the error on peaking background is due to the MC statistics and to the uncertainty on the relevant $\overline{D}^0$ and D_s^+ branching fractions; the uncertainty on the combinatorial background is estimated using the ΔE sideband ($|\Delta E| > 200$ MeV) as an alternative way of computing the number of background events under the m_{ES} peak. Several systematic uncertainties in

the full reconstruction are in common with the partial reconstruction analysis, and therefore cancel in the ratio of Eq. 3. All remaining sources are listed in the last column of Table I.

We repeated both the partial and the full reconstruction analyses on generic MC samples consisting of $B^0\overline{B}^0$, B^+B^-, and low-mass $q\overline{q}$ events, finding no bias. The result is also stable over different data-taking periods.

In summary, we have measured the $B^0 \rightarrow D^{*-}D_s^{*+}$ branching fraction

$$\mathcal{B}(B^0 \rightarrow D^{*-}D_s^{*+}) = (1.88 \pm 0.09 \pm 0.17)\%, \quad (5)$$

where the first uncertainty is statistical and the second is systematic. This result is independent of the partial decay rates of the D_s^+ mesons. It is consistent with a previous BABAR measurement [2] and with the world average, and reduces the total uncertainty by a factor of about three. The measurement is in agreement with the predictions of the factorization model $\mathcal{B}(B^0 \rightarrow D^{*-}D_s^{*+})_{\mathrm{theor}} = (2.4 \pm 0.7)\%$ [4].

We have measured the branching fraction of $D_s^+ \rightarrow \phi\pi^+$ decay:

$$\mathcal{B}(D_s^+ \rightarrow \phi\pi^+) = (4.81 \pm 0.52 \pm 0.38)\%. \quad (6)$$

This result represents an improvement by about a factor of two over previous measurements [1, 16].

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